

# The Response of the Upper Ocean to Monsoonal Forcing

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## LONG-TERM GOAL

The ultimate goal of my research is a complete characterization of the upper ocean's response to atmospheric forcing. The forcing takes place through surface fluxes of heat, fresh water and momentum. The response may be local and direct, or may be modified by advection and wave propagation.

## OBJECTIVES

The scientific objective of my effort is the observation of the oceanic response to the Arabian Sea monsoons. The primary technological objective is the development of a light-weight meteorological package for deployment on a surface mooring. The Arabian Sea is an attractive region for an air-sea interaction experiment because of the strength and steadiness of the monsoons. The wind-stress spectrum is more energetic at low frequencies in the Arabian Sea than in mid-latitude locations where the forcing is dominated by storms. The Arabian Sea ARI thus provides an interesting contrast to previous experiments done at higher latitudes such as LOTUS, FASINEX, and Ocean Storms.

## APPROACH

My experimental approach has been to deploy two surface moorings as part of a five-mooring array in collaboration with R. Weller of WHOI and C. Eriksen of UW. An SIO mooring includes a surface buoy carrying a meteorological package (MARMET) measuring wind speed and direction, short-wave radiation, air and sea temperatures, and atmospheric pressure. The buoy bridle holds a downward looking 300 kHz Acoustic Doppler Current Profiler (ADCP) measuring horizontal velocity in 4 m bins down to 120 m. Temperature recorders are positioned at 10 m intervals in the upper 50 m and 20 m intervals from 50 to 150 m. My approach in analyzing the data is to use appropriate statistical methods to isolate the ocean's response to the monsoons.

## WORK COMPLETED

The two moorings were successfully deployed during a cruise in October 1994, turned around in April 1995, and recovered in October 1995. Overall data recovery was excellent. All meteorological data on all buoys were returned except for wind during the first deployment of the southern buoy. The wind sensor electronics failed during a strong storm, presumably due to a lightning strike. The overall data return of meteorological variables was thus 95%. The ADCPs worked flawlessly so that horizontal velocity data return was 100%. All temperature recorders worked perfectly during the first six months. Unfortunately, we suffered some failures and losses during the SW monsoon. Five recorders were

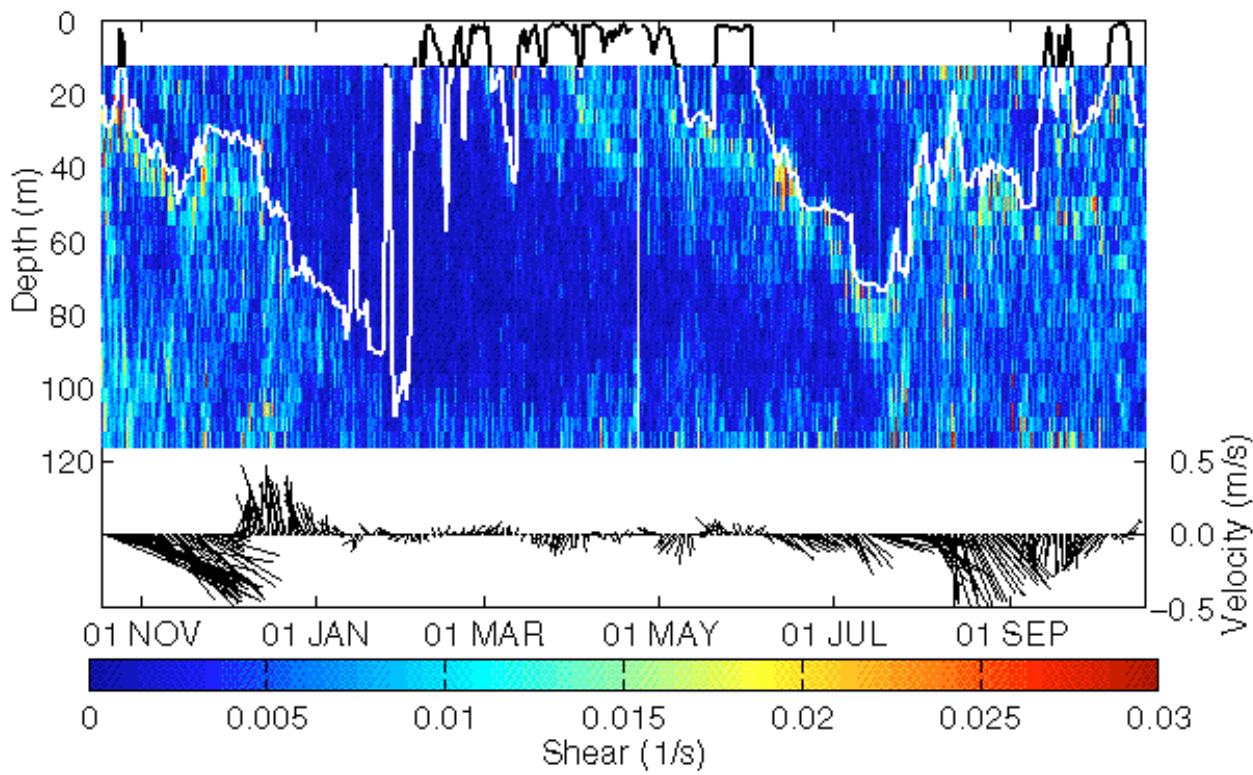
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stripped from the mooring line on the north mooring, two recorders had short records, and one was recovered with the end caps and electronics gone. In spite of the problems, overall temperature data return was 82%. Weighting meteorological variables, currents, and temperatures equally, the data return on the two SIO moorings was 92%. An initial report on the unprecedented one-year moored observations has been published in (Rudnick et al. 1997).

## RESULTS

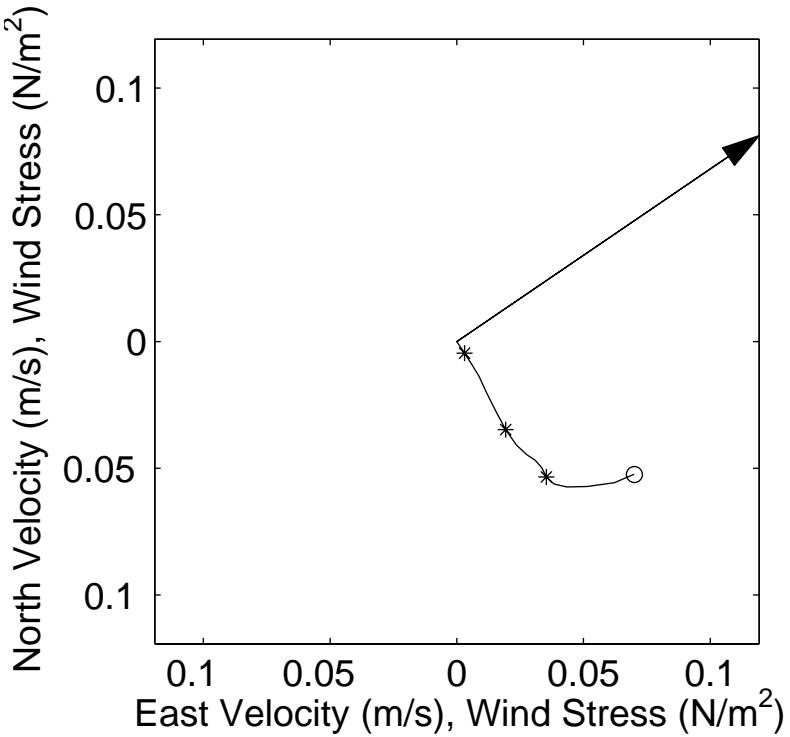
A fairly complete characterization of the ocean's response to the monsoon has been achieved. The winds were remarkably steady during both monsoons, with almost no variability in direction during the SW monsoon. Typical wind speeds were several meters per second during the NE monsoon, while speeds sometimes exceeded 15 m s<sup>-1</sup> during the SW monsoon. Because the wind stress is a quadratic function of wind speed, the peak wind stress during the SW monsoon was about four times that during the NE monsoon. The air was generally cooler than the sea surface except during the SW monsoon, when warm air was advected northward from Africa. Two periods of low sea surface temperature occurred during the year. The low in summer is unique to the Arabian Sea, and is due to a combination of entrainment, advection, and surface cooling. The net heat flux was strongly negative during the NE monsoon, primarily because of latent heat loss associated with cool northerly winds. Two periods of heat loss during the SW monsoon were caused by latent heat losses and a reduction of insolation due to clouds.

Two periods of mixed-layer deepening coincided with the onsets of the two monsoons (Figure 1). The mixed layer was deeper during the NE monsoon than during the SW monsoon because of latent heat loss and strong convection. It is worth noting that convection is more efficient at creating a deep mixed layer than is wind stirring. Restratiification was apparent during the inter-monsoon periods. The maximum in shear, as measured by the ADCP in 4 m bins, traced the base of the thermal mixed layer. This maximum was most striking during mixed-layer deepening at the onset of the monsoons. There was noticeably less shear in the mixed layer than in the seasonal thermocline, as might be expected. Shear beneath the mixed layer on 1 August was coincident with a change in current direction; this shear was likely geostrophically balanced. The ADCP is clearly superior than discrete mechanical current meters at measuring shear, and the examination of shear is a focal point of scientific analysis.



**Figure 1.** A time-depth section of shear, a time series of mixed-layer depth, and a velocity stick plot. The 4-hour-average shear magnitude is plotted as a color image, with a vertical resolution of 4 m. The mixed-layer depth (black and white line) is defined by a  $0.1^{\circ}\text{C}$  difference from the surface. Daily averaged velocity at 20 m depth is represented by sticks with upward being to the north. Note the region of high shear beneath the relatively unsheared mixed layer. The velocity has temporal variability unrelated to local wind.

One-dimensional budgets have been remarkably successful at describing oceanic response to the atmosphere. The first stage of our analysis is addressing the one-dimensional budget of momentum through a careful examination of shear. The steady one-dimensional momentum balance of Coriolis force and turbulent stress parameterized with a constant eddy viscosity results in the well-known Ekman spiral (Ekman 1905). The mean velocity relative to 72 m over the onset of the monsoon (May 1 - July 15) reveals a spiral (Figure 2). The transport integrated from the surface down to 72 m agrees with the theoretical Ekman transport to within 1% in magnitude and  $6^{\circ}$  in direction. This agreement with steady Ekman dynamics has prompted the investigation of how this balance is established. A particularly important issue is to determine how much of the wind driven flow occurs beneath the mixed layer. The mean mixed layer depth over the monsoon onset is 34 m, so much of the wind-driven transport is occurring beneath the mixed layer. Individual two-day averages of shear have been used to examine the temporal variability of wind-driven flow. The remarkable result is that the Ekman relation holds even on this short time scale. We have made movies of Ekman spirals that respond instantaneously to changes in the strength of the unidirectional monsoon wind.



**Figure 2.** The wind-driven spiral during the onset of the SW monsoon. The wind stress (plotted as a vector) and the velocity relative to 72 m (plotted as a curve) are averaged over the period May 1 - June 15. The circle indicates the 8 m velocity, and asterisks are plotted every 20 m (28, 48, and 68 m). The spiral turns rapidly to the right from 8 m to 20 m, and is relatively uniform in direction deeper. The integrated velocity agrees with the theoretical Ekman transport to within 1% in magnitude and 6° in direction.

Much of the shear at the mixed layer base is inertial. As shown graphically during the Ocean Storms Experiment (D'Asaro et al. 1995), beams of near-inertial energy can penetrate well beneath the mixed layer. We have found that wavelet analysis (Farge 1992) is an especially useful tool for isolating inertial energy as a function of time. We are nearing completion of a study of inertial shear using wavelets.

## IMPACT/APPLICATION

These observations comprise the first year-long time series of the oceanic response to the Arabian Sea monsoons. The Arabian Sea provides a nearly ideal laboratory for studying the response to a steady wind. The siting of experiments provides what little control oceanographers have over their experiments. In this case the steady wind produced convincing evidence of a nearly instantaneous Ekman spiral.

## TRANSITIONS

Our marine meteorological system MARMET forms the central suite of meteorological measurements on the SIO Marine Observatory "monster buoy."

## RELATED PROJECTS

The effects of horizontal advection are being addressed in three-dimensional budgets in a collaboration with R. Weller and graduate student A. Fischer, with Fischer taking the lead. A presentation was given at the 1998 Ocean Sciences meeting.

A collaboration has begun with Piotr Flatau and Maria Flatau on the coupled response of the atmosphere and ocean during the monsoon onset. The Flataus' work is funded by NSF and NOAA. A presentation was given at the 1998 Ocean Sciences meeting.

A final collaborative project involves the comparison of the moored data to a numerical model of the Indian Ocean being run by N. Rix at Kiel. The model is the GFDL MOM with  $1/3^\circ$  horizontal resolution and 10 m vertical resolution. The initial goal is to tune the mixed-layer parameterizations in the model. The model will then be used to examine the heat content of the upper waters throughout the Arabian Sea.

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